BEYOND THE DECADAL STUDY: RPS FOR SCIENCE MISSIONS TO COME.

Nuclear and Emerging Technologies for Space

February 2017

David Woerner
Jet Propulsion Laboratory/California Institute Of Technology

Future Planetary Missions*

	Mercury	Venus	Earth's Moon	Mars	Jupiter	Io	Europa	Ganymede	Saturn	Enceladus	Titan	Uranus	Neptune	Triton	Plutoid Pluto	Asteroids	Comets
Flyby 1	Mariner 10 MESSENGER	Mariner 2, 5, 10 Venera 11-14 Galileo Cassini MESSENGER Akatsuki	Luna 1, 3 Pioneer 4 Zond 3, (5), 6, 7, 8 Apollo 13 Hiten	Mariner 4 Mariner 6, 7 Mars 4 Mars Observer (Rosetta)	Pioneer 10 Pioneer 11 Voyager 1 Voyager 2 Cassini New Horizons	Galileo	Galileo	Galileo	Pioneer 11 Voyager 1 Voyager 2 Cassini	Voyager 2	Voyager 2 Cassini	Voyager 2	Voyager 2	Voyager 2	New Horizons*	NEAR Shoemaker Rosetta Galileo (Cassini) Deep Space 1 Rosetta New Horizons (KBO)	ICE (ISEE-3) VeGa 1, 2 Sakigake, Suisei Giotto Deep Space 1 Stardust & Stardust-NeXT Deep Impact & EPOXI (Galileo, Ulysses)
Orbit 2	MESSENGER*	Venera 9, 10, 15, 16 Pioneer 12 (PV 1) Magellan Venus Express Akatsuki (2016)*	Luna 10-12, 14, 19, 22 Lunar Orbiter 1-5 Apollo 8, 10, 11, 12, 14, 15, 16, 17 Clementine Lunar Prospector SMART-1 Hiten, SELENE (Kaguya)+Okina & Ouna Chang'e 1 & Chang'e 2 Chandrayaan 1 LRO, GRAIL, LADEE*	Mariner 9 Mars 2, 5 Viking 1, 2 Phobos 2 Mars Global Surveyor Mars Odyssey Mars Express Mars Reconnaisance Orbiter MAVEN*	Galileo Juno				Cassini							NEAR Shoemaker Hayabusa Dawn	Rosetta
Lander 3		Venera 3 (crash landing) Venera 7-10, (11, 12), 13, 14 Pioneer 13 (PV 2; 1 entry survivor) VeGa 1, 2	Ranger 7, 8, 9 Luna 2, 9, 13 Surveyor 1, 3, 4, 5 LCROSS	Mars 2 (crash landing) Mars 3 (no useful data) Viking 1, 2 Mars Pathfinder Phoenix	Galileo Probe						Huygens					NEAR Shoemaker	Deep Impact Philae (2014)*
Rover 4			Apollo 11, 12, 14 (legs) Apollo 15, 16, 17 (wheels) Lunakhod 1, 2 (Luna 17, 21)	Sojourner MER Spirit, MER Opportunity MSL Curiosity*													
Return Samples 5			Apollo 11, 12, 14, 15, 16, 17 Luna 16, 20, 24													Hayabusa Hayabusa 2* OSIRIS REx*	Stardust

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- **Radioisotope power** and the development of critical technologies will be needed for all types of missions

*Reference: *RPS Mission Pull*, Dudzinski, L, Panel at the 10th International Energy Conversion Engineering Conference, August 1, 2012

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What to pick? So many choices…just from the last Decadal Survey

1. Chiron Orbiter Mission Concept Study
2. Comet Surface Sample Return Mission Concept Study
3. Cryogenic Comet Nucleus Sample Return Mission Technology Study
4. Enceladus Flyby & Sample Return Concept Studies
5. Enceladus Orbiter Concept Study
6. Ganymede Orbiter Concept Study
7. Io Observer Concept Study
8. Jupiter Europa Orbiter (component of EJSM) Concept Study
9. Lunar Geophysical Network Concept Study
10. Lunar Polar Volatiles Explorer Mission Concept Study
11. Mars 2018 MAX-C Caching Rover Concept Study
12. Mars 2018 Sky Crane Capability Study
13. Mars Geophysical Network Concept Study
14. Mars Geophysical Network Options
15. Mars Polar Climate Concepts
16. Mars Sample Return Lander Mission Concept Study
17. Mars Sample Return Orbiter Mission Concept Study
18. Mercury Lander Mission Concept Study
19. Near Earth Asteroid Trajectory Opportunities in 2020-2024
20. Neptune-Triton-Kuiper Belt Objects Mission Concept Study
21. Saturn Atmospheric Entry Probe Mission Concept Study
22. Saturn Atmospheric Entry Probe Trade Study
23. Saturn Ring Observer Concept Study
24. Small Fission Power System Feasibility Study
25. Titan Lake Probe Concept Study
26. Titan Saturn System Mission
27. Trojan Tour Concept Study
28. Uranus and Neptune Orbiter and Probe Concept Studies
29. Venus Climate Mission Concept Study
30. Venus Intrepid Tessera Lander Concept Study
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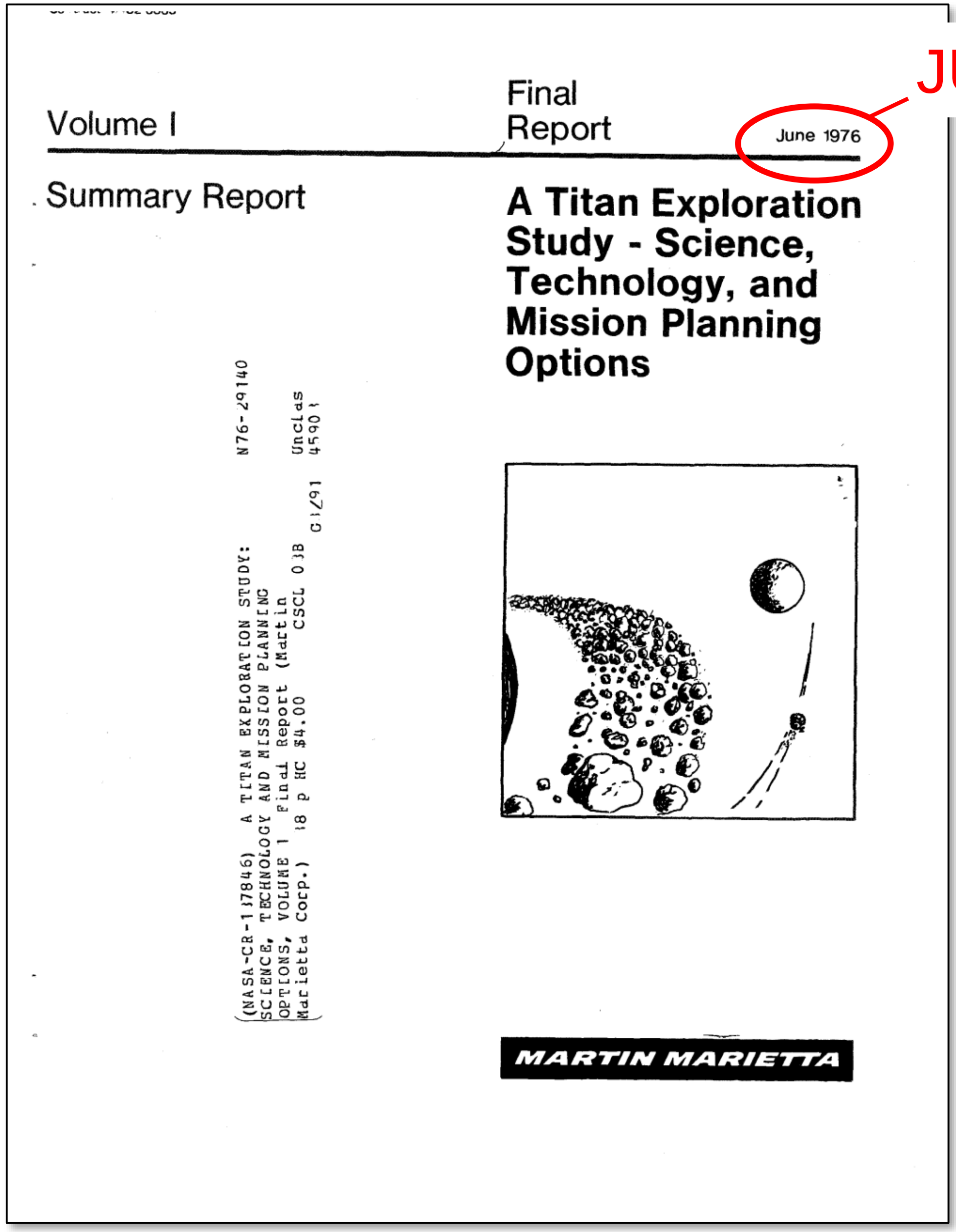
The community has had their eyes on Titan for a long time.



Volume I

Final Report

June 1976

Summary Report

A Titan Exploration Study - Science, Technology, and Mission Planning Options

(NASA-CR-137846) A TITAN EXPLORATION STUDY: SCIENCE, TECHNOLOGY AND MISSION PLANNING OPTIONS, VOLUME 1 Final Report (Martin Marietta Corp.) 18 p HC $4.00 CSCL 03B N76-29140 Unclas G3/91 45901

MARTIN MARIETTA

JUNE 1976

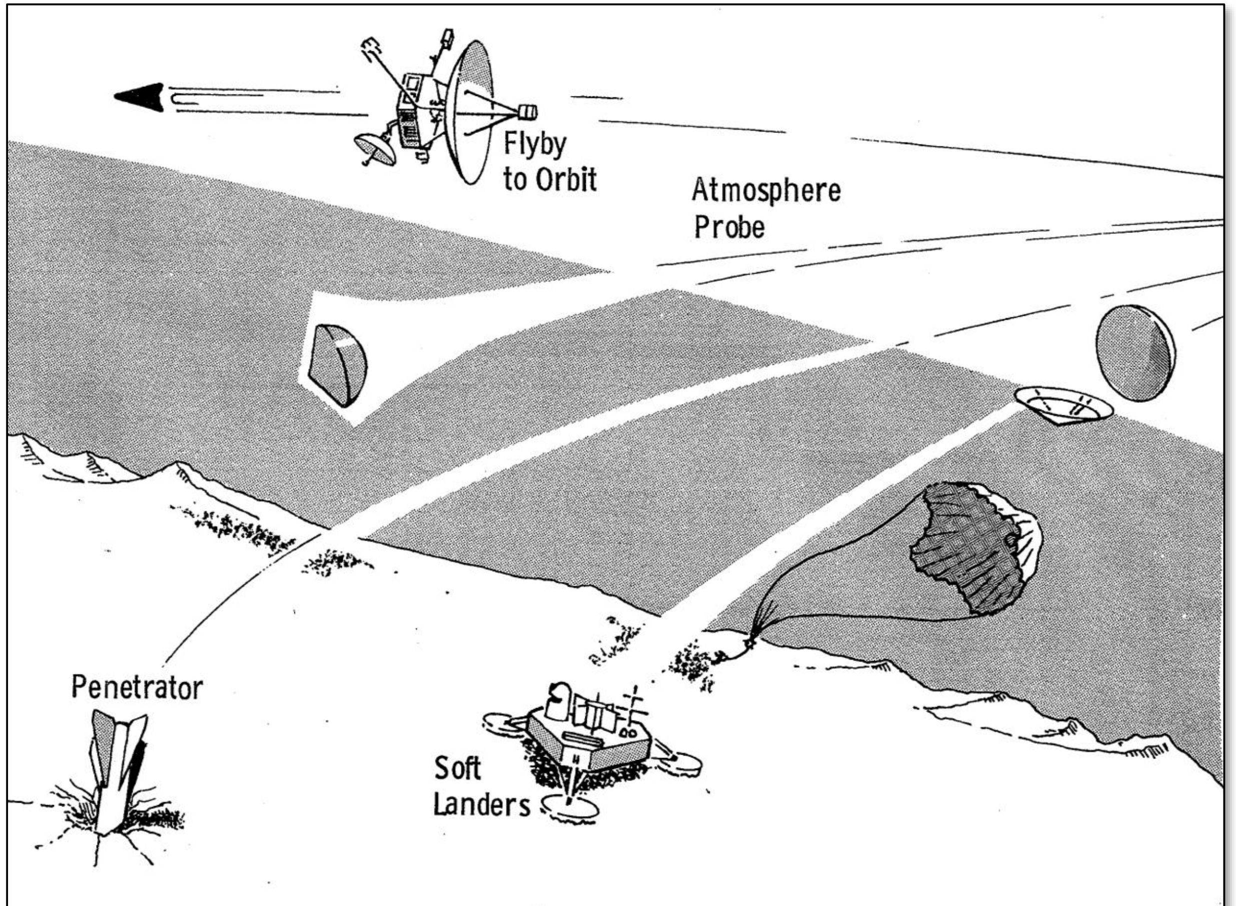
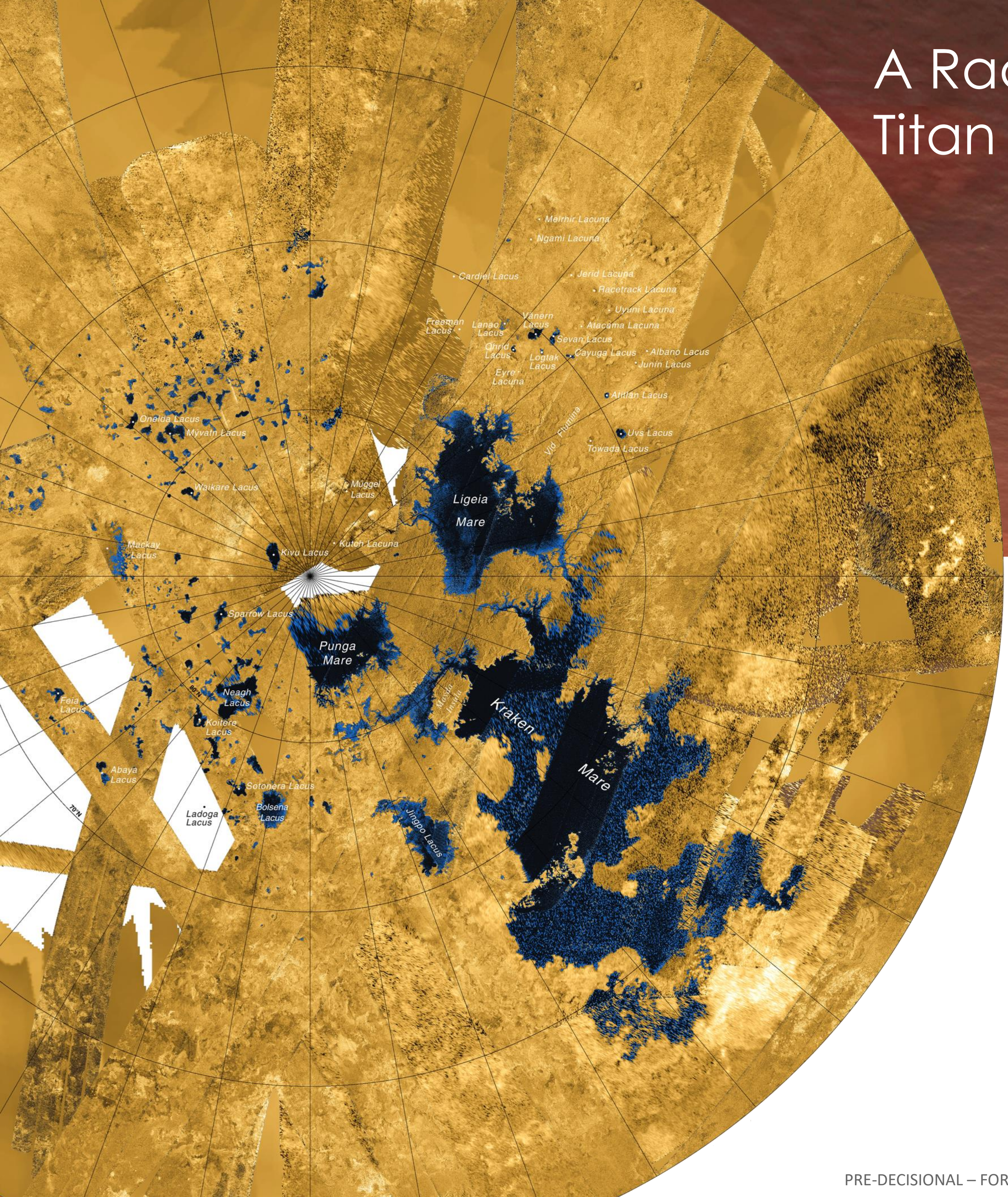
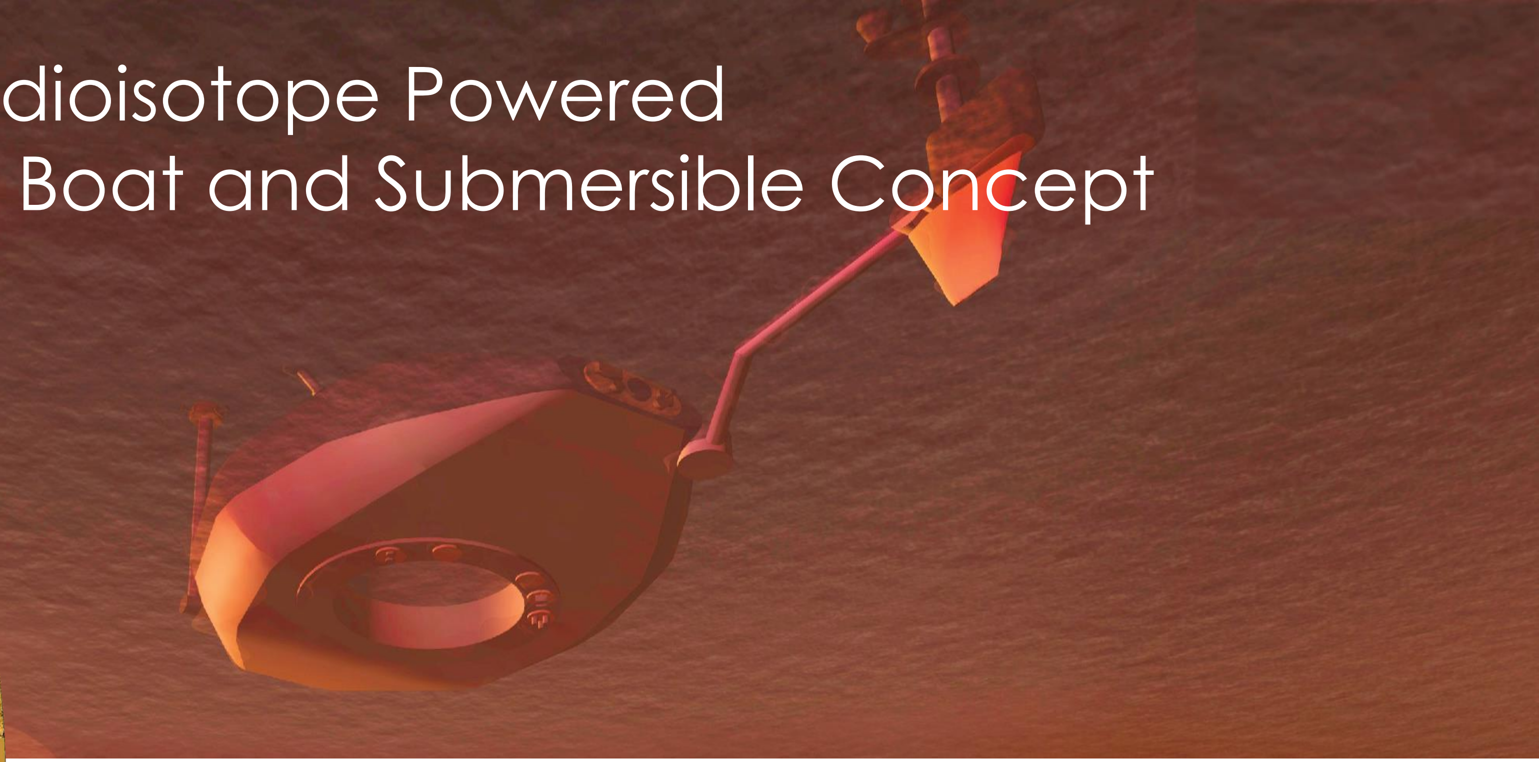


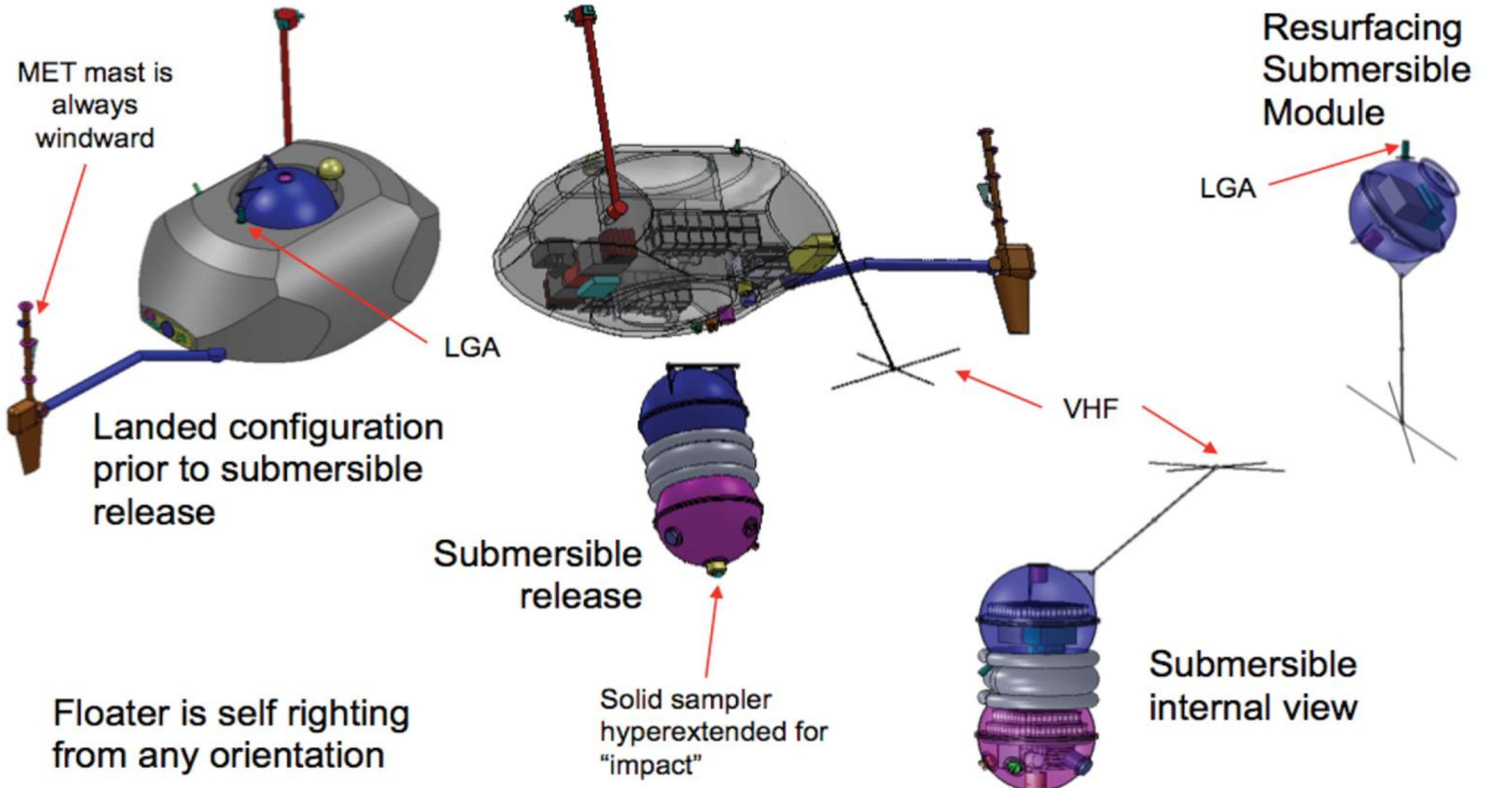
Fig. 2 Titan Exploration Mission Modes

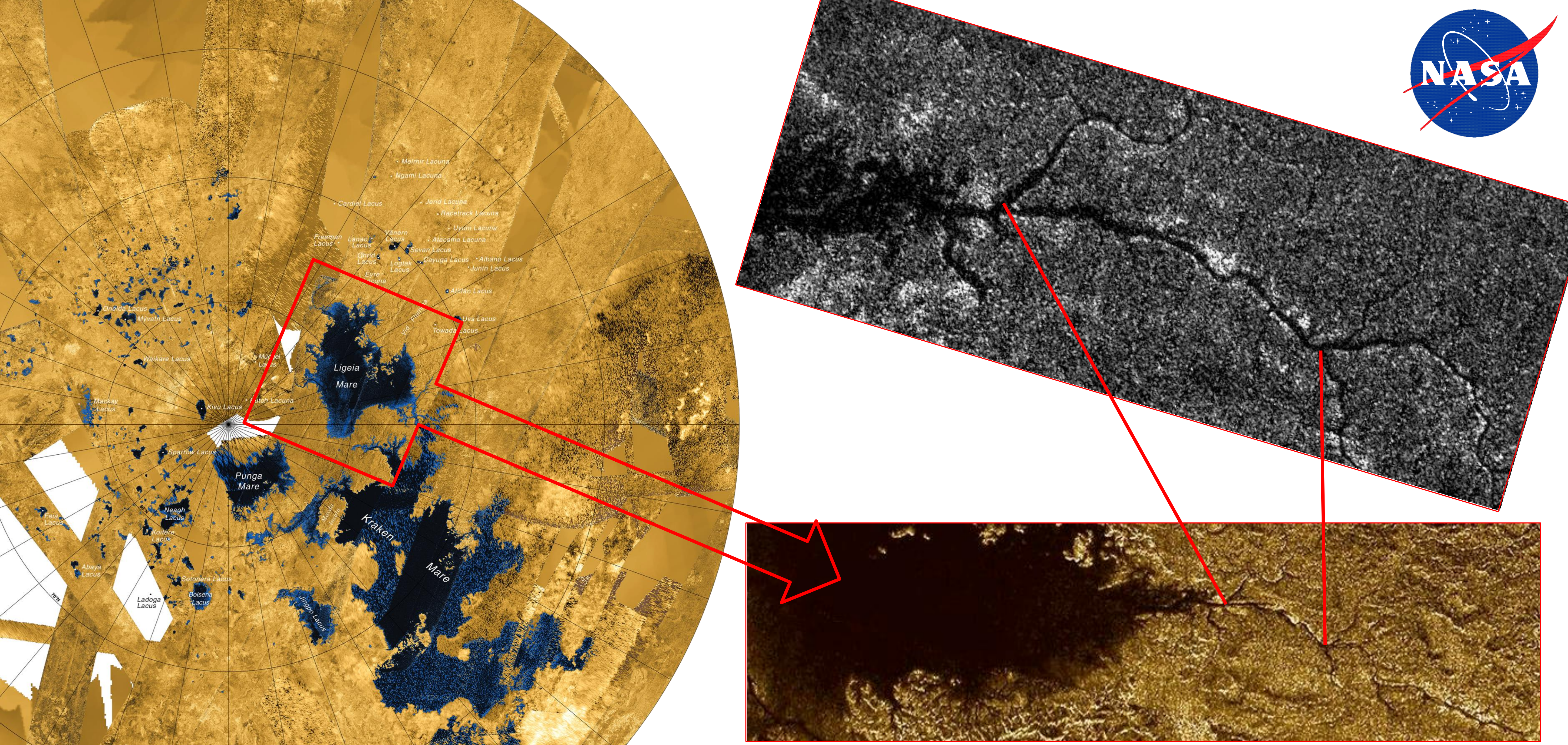
At least 3 concepts are missing from this cartoon. Can you spot 3? Balloons, airplanes, and boats. Boats could not have been in this report as it was not until 1995 that Hubble and other measurements confirmed the existence of liquid methane.

A Radioisotope Powered Titan Boat and Submersible Concept



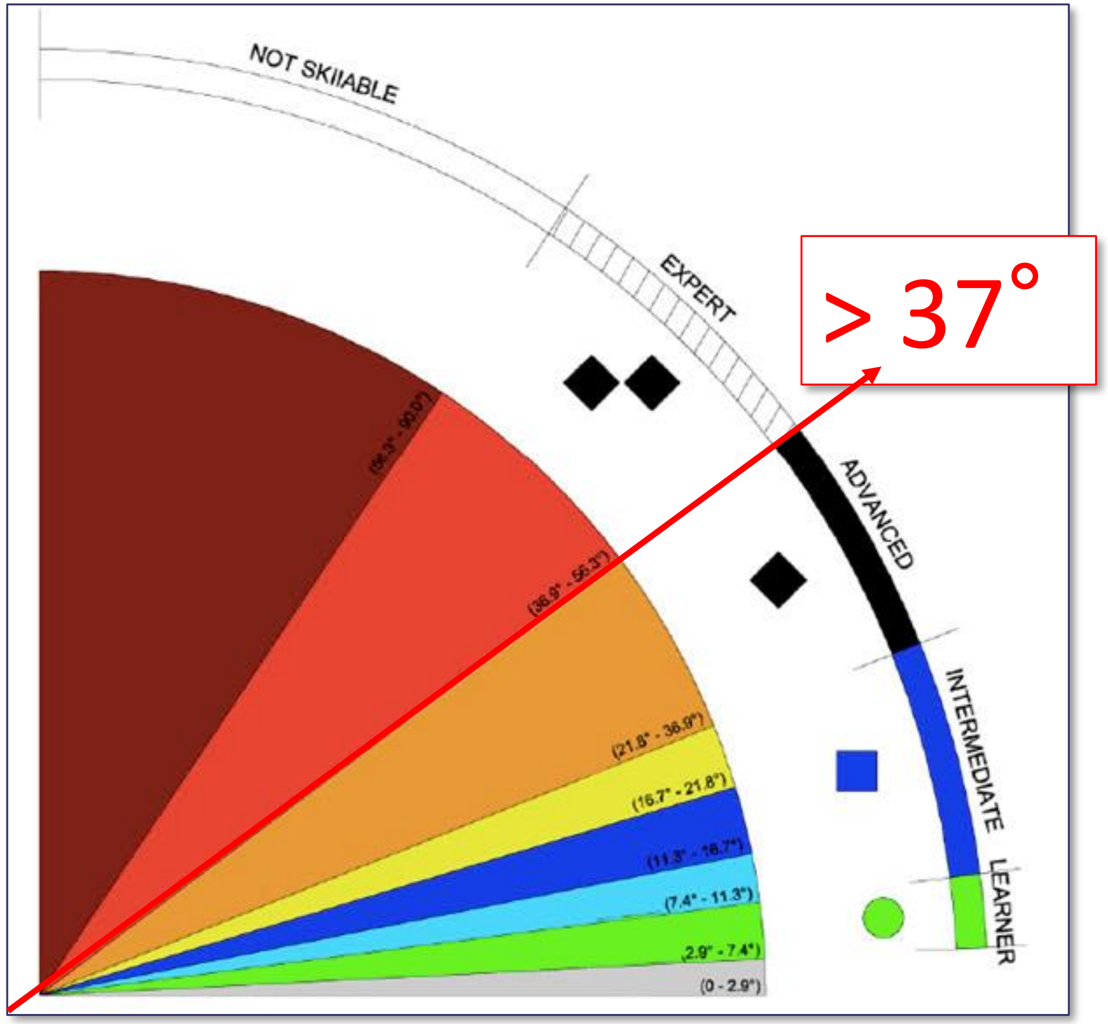






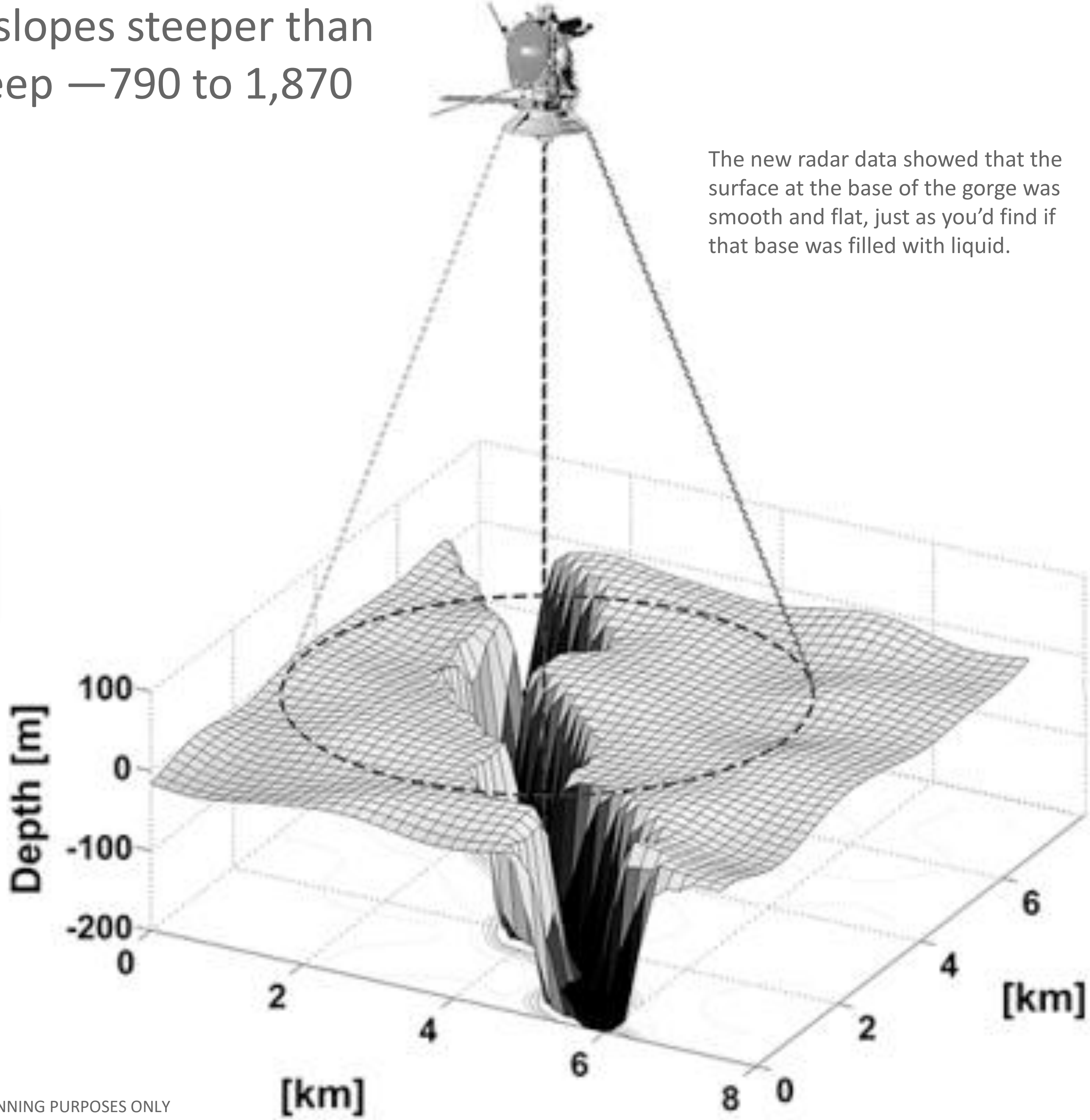
Ref: http://www.esa.int/spaceinimages/Images/2016/09/Methane-flooded_canyons_on_Titan

Cassini observations reveal channels — narrow canyons, generally less than half a mile wide, with slopes steeper than 40 degrees. The canyons also are quite deep —790 to 1,870 feet from top to bottom.



http://www.alpineinfusion.com/a-rough-guide-to-ski-slope-safety-ratings/

The new radar data showed that the surface at the base of the gorge was smooth and flat, just as you'd find if that base was filled with liquid.



A Radioisotope Powered Boat – Characteristics of RPS

Moderate power source required, ~120-250 We	Energy driven science rather than power, however, propulsion might bias the design towards power
Rugged against Entry, Descent, and Landing	Although can be less severe than Mars
Operates in vacuum and planetary atmospheres	Cruise and lake operations
Compact; operates without fins a plus	Minimizes volume
Provides continuous waste heat and heat management loops	Keeps electronics warm
Long-lived power source	32 days between comm-relay passes

Ocean Worlds…

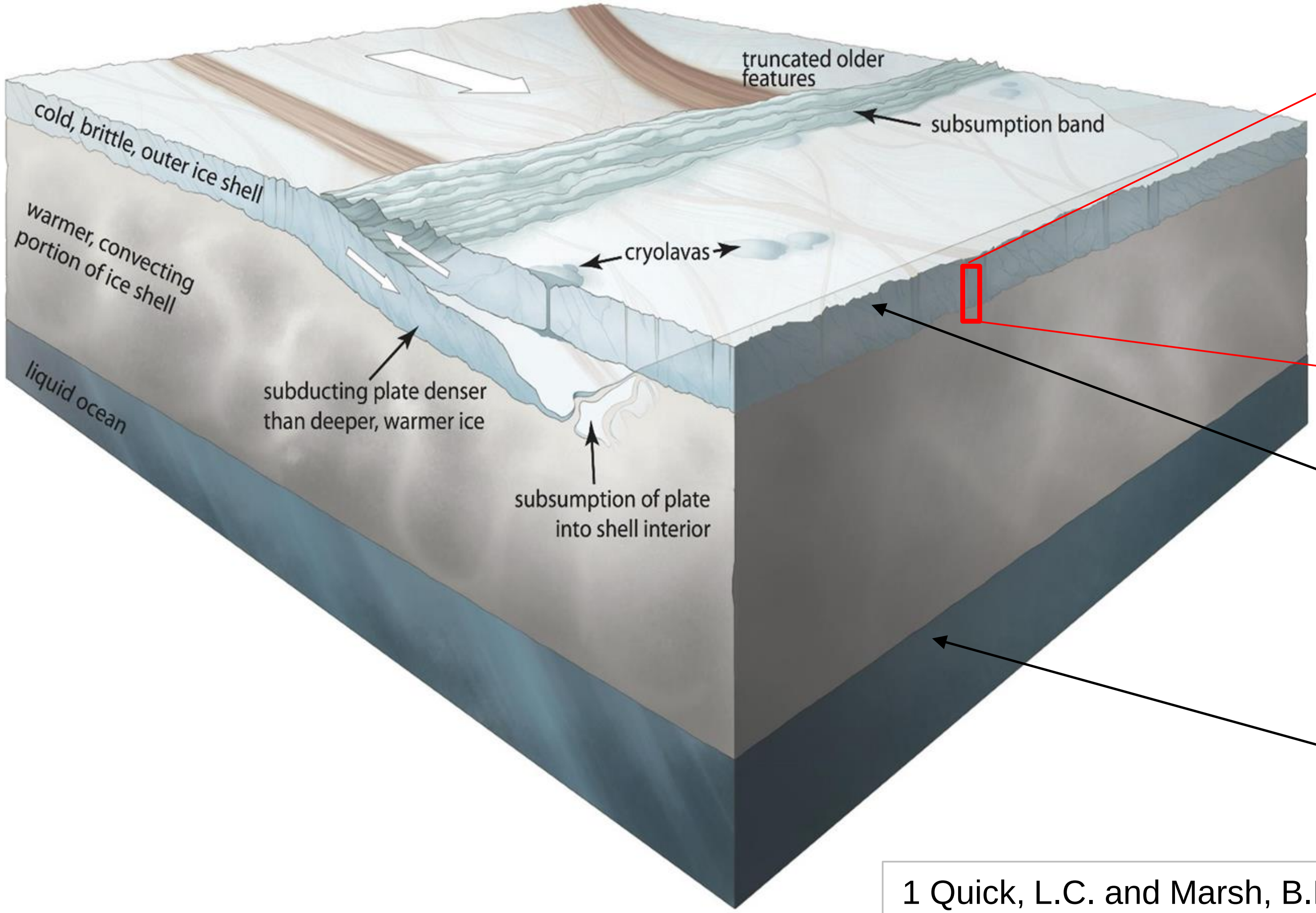
- OPAG, August 12, 2016, *Roadmaps to Ocean Worlds* was discussed with Amanda Hendrix and Terry Hurford leading.

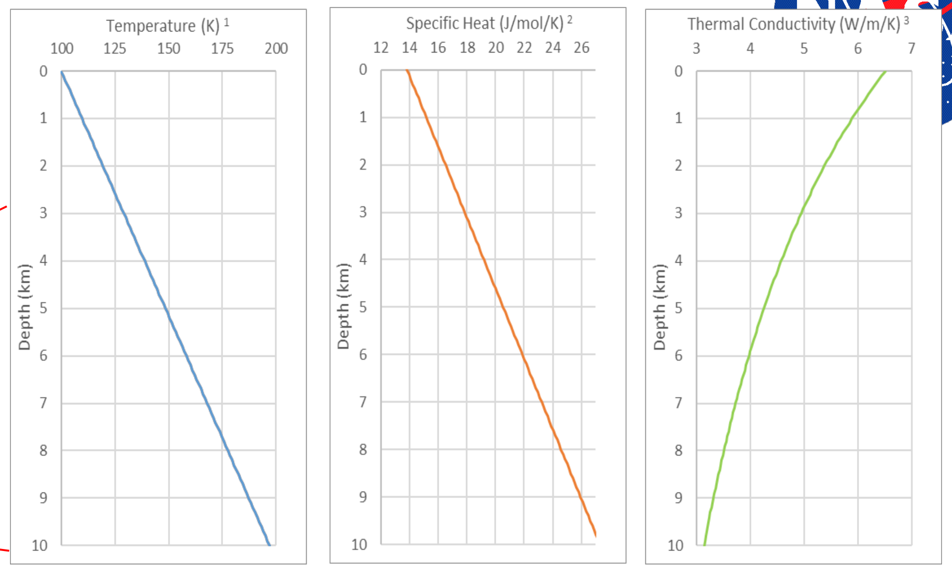
- From the Commerce, Justice, Science, and Related Agencies Appropriations Bill, 2016 –

  "…The Committee **directs NASA to create an Ocean World Exploration Program** *whose primary goal is to discover extant life* on another world using a mix of Discovery, New Frontiers and flagship class missions consistent with the recommendations of current and future Planetary Decadal surveys."

- A Concluding Chart:
  - Current & Future Activities
    - » In work: Identify mission concepts and measurements needed to address science questions

Europa Melt Probe Concept – Likely Environment





Cold (~100K), sublimation regime
- no liquid phase near sfc
- 0 pressure

~0C solid/liquid, high P

1 Quick, L.C. and Marsh, B.D., 2016. Heat transfer of ascending cryomagma on Europa. Journal of Volcanology and Geothermal Research, 319, pp.66-77.
2 Murphy, D. & T. Koop, 2005, Review of the vapour pressures of ice and supercooled water for atmospheric applications, Q. J. R. Meteorol. Soc., v131, pp. 1539–1565
3 Slack, G., 1980, Thermal conductivity of ice, Phys. Rev. B, v22, No. 6.
4. Image ref: (Kattenhorn, S.A. and Prockter, L.M., 2014. Evidence for subduction in the ice shell of Europa. *Nature Geoscience*, *7*(10), pp.762-767.)
http://photojournal.jpl.nasa.gov/

Ocean Worlds…

- The potential (water) ocean worlds have thick ice crusts encasing the oceans that create very high pressures both in the ice and in the surmised oceans. As examples,

Ocean Worlds - Subsurface

Body	AU	Sfc. T (K)	Ocean T (K)	Ocean P., max (atm)	Ocean Composition
Ganymede	5.20	110	273	11290	H_2O
Callisto	5.20	134	273	3855	H_2O
Europa (equator)	5.20	102	273	1745	H_2O
Mimas	9.52	141	273	63	H_2O
Enceladus	9.52	75	273	38	H_2O
Titan - Sfc	9.52	94	94	3	C_2H_6
Titan - Interior	9.52	94	273	4003	H_2O
Triton	30.09	38	230	3014	H_2O / NH_3
Ceres	2.77	155	-	0	H_2O ?
Pluto	39.75	44	230	2233	H2O ?

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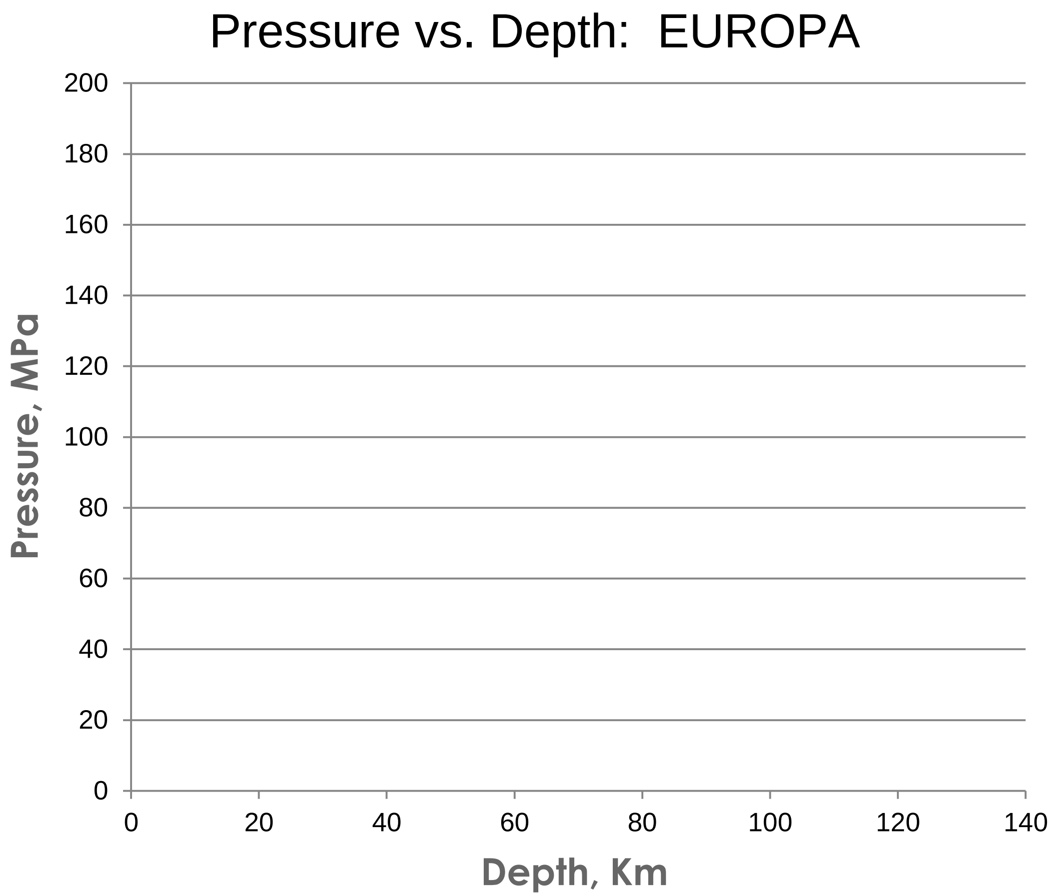
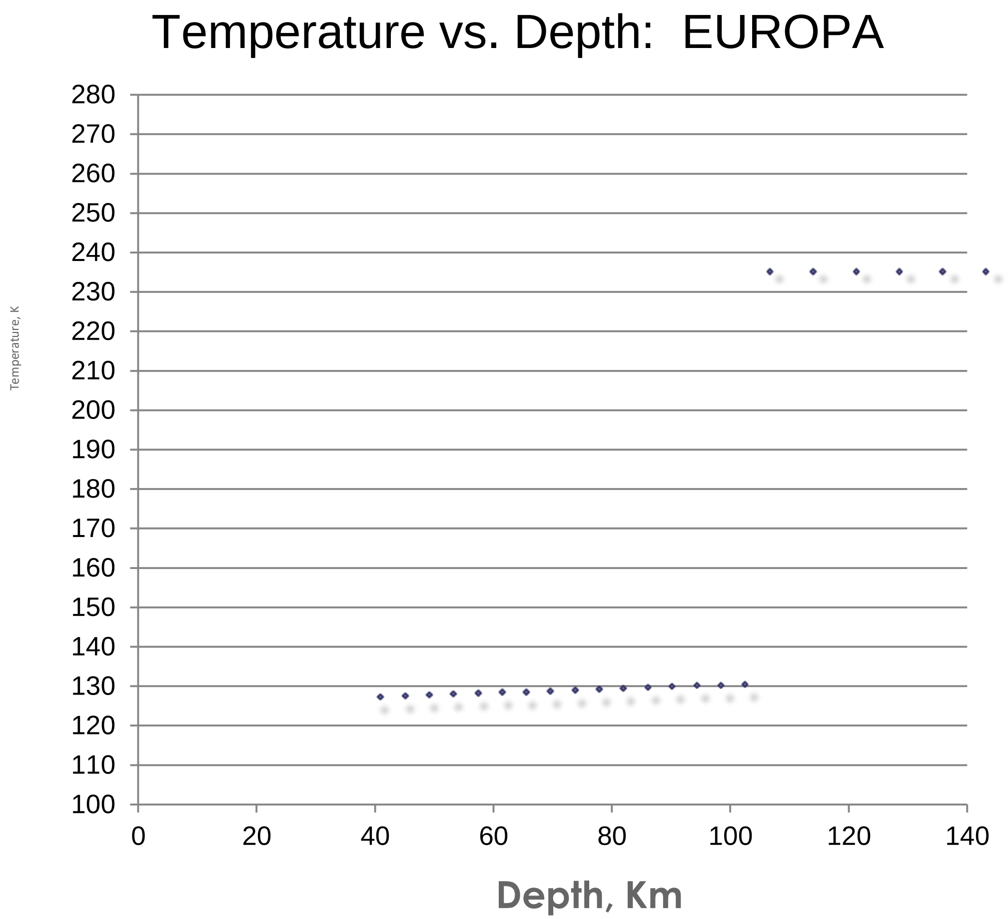
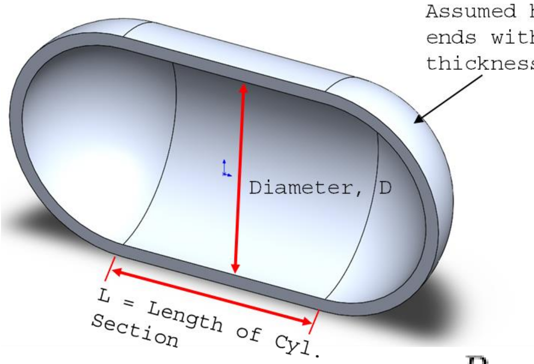




Models courtesy Steve Vance, JPL Div. 32

Pressure Vessels for Subsurface Mission Concepts

- For Ice Sheet Depths (ice-water interface)
- Cylindrical pressure vessel with hemispherical caps and water tight feedthroughs
- Vacuum inside vessel
- Fits MMRTG and eMMRTG
- No factor of safety in these numbers

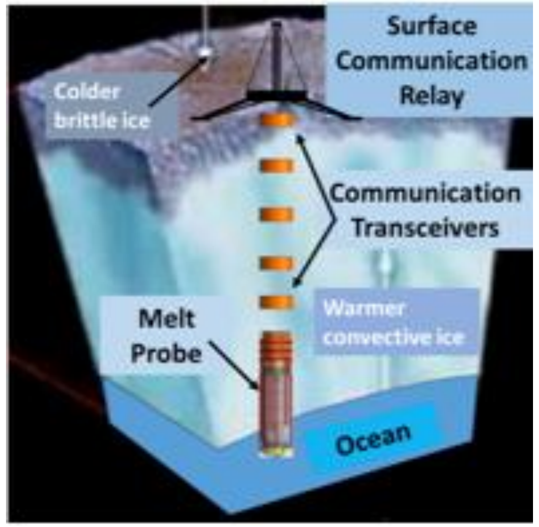


$$P_{cr} = \frac{2E}{(1-\nu^2)}\left(\frac{t}{d}\right)^3$$

ν = Poisson's Ratio
E = Elastic Modulus
t = shell thickness
d = shell outer diameter
P_{cr} = Buckling Pressure

S. Chattopadhyay, *Pressure Vessels, Design and Practice*, CRC Press 2004, Chapter 5

	composition	g (m/s2)	h max (km)	fluid density (kg/m3)	P max (atm)	shell thick Al (cm)	shell mass Al (kg)
Earth	H2O	9.8	11	1000	1064	4.31	202
Ganymede	H2O	1.43	144	1000	2032	5.64	275
Callisto	H2O	1.24	150	1000	1836	5.40	261
Europa	H2O	1.31	30	1000	388	2.90	130
Mimas*	H2O	0.064	100	1000	63	1.49	64
Enceladus	H2O	0.133	40	1000	53	1.39	59
Titan - Lakes	C2H6	1.352	0.3	650	3	0.49	20
Titan - Subsurface Ocean	H2O	1.352	20	1000	267	2.52	111
Triton	H2O/NH3	0.779	200	1000	1538	5.02	240
Ceres*	H2O/NH3	0.28	?	?		0.00	0
Pluto	H2O/NH3	0.62	260	1000	1591	5.09	244



A Radioisotope Powered Melt Probe – Characteristics of RPS

Moderate electrical power source, ~100-200 We	Energy-driven science, burst driven communications
Operates in vacuum and planetary atmospheres	Cruise and operations in ice
Compact; operates without fins a plus;	High-density and/or minimal cross-section maximizes penetration rate
Rugged against landing shocks/loads years after fueling	Missions to air-less bodies have a landed-mass disadvantage, this likely counters that
Long-lived power source	Ice penetration likely to take years
Amenable to pressure vessels and ice penetration	Heat transfer within pressure vessel uncomplicated. Form-factor closely matches optimal penetration shape or RPS is compliant with vessel
Provides continuous, uniform waste heat (2000 – 4000Wth), external heat management loops, and other heat transfer mechanisms	Does not convert heat into electricity only to convert back into heat or actuation cycles

What mission and destination to pick? So many choices…

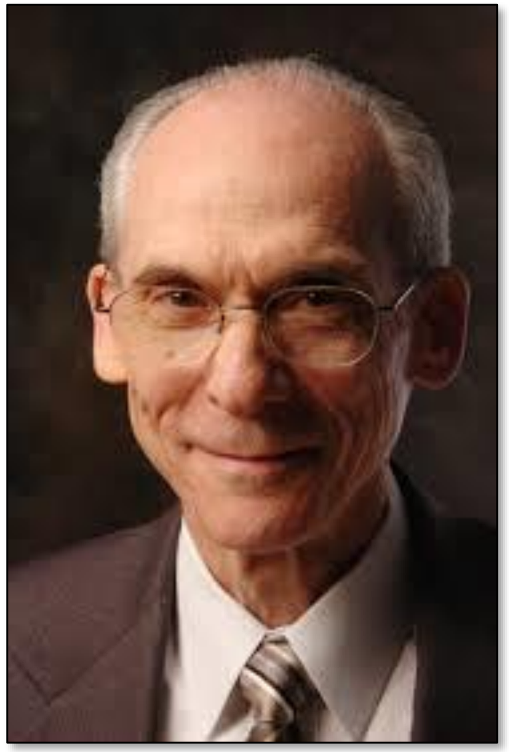
- Are you after better science?
- What can an RPS do for you?
  - Enhance a mission
  - Enable a mission
  - Increase science return
  - Boost the quality of science returned
    - » In space for natural phenomenon undergoing changes over years and decades
    - » In space for repeated measurements
  - Boost the quantity of science returned
    - » Increased chance of extended mission(s)
    - » More PhDs
  - Sidestep a Philae-like demise
  - Extend a Huygens-like mission

Mission	RTG type (number)	Launch Year	Mission Length
Pioneer 10	SNAP-19 RTG (4)	1972	34
Pioneer 11	SNAP-19 RTG (4)	1973	35
Viking 1	SNAP-19 RTG (2)	1975	> 6
Viking 2	SNAP-19 RTG (2)	1975	> 4
Voyager 1	MHW-RTG (3)	1977	39+
Voyager 2	MHW-RTG (3)	1977	39+
Galileo	GPHS-RTG (2)	1989	14
Ulysses	GPHS-RTG (1)	1990	18
Cassini	GPHS-RTG (3)	1997	~20
New Horizons	GPHS-RTG (1)	2005	10+
MSL	MMRTG (1)	2011	5+
*Mars 2020***	*MMRTG (1 baselined)*	*2020*	*(5)*

Thank you

Mark your calendar

Abstracts due March 6, 2017



Keynote: Dr. Edward Stone